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INVESTIGATION OF AZIMUTHAL INHOMOGENEITY OF PLASMA IN A HOMOPOLAR

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E.M.Drobyshevskiy, S.I.Rozov, and A.M.Studenkov[1)]

ABSTRACT. The inhomogeneity of a plasma in azimuthal direction was investigated in a homopolar machine placed in a solenoid, using probes, photomultipliers, and oscillographs for determining the cause of blocking of the free flow of azimuthal current. The formation of current canals was found responsible for the generation of forces and discharges, resulting in a Hall electric field which decreases in azimuthal direction and produced breakdown and formation of new cathode spots. It is concluded that the velocity of the plasma canal is limited mainly by the rate of displacement of the cathode spot at the electrode.

1. A homopolar machine is a system for the stationary acceleration of plasma in crossed fields, which has no design limits as to the flow of the Hall current in azimuthal direction. For the parameters of the discharge under consideration in the system (H = 200 - 2500 oe; I = 2 - 4 amp; p = 0.1 - 1.0 mm Hg), the density of the Hall current j_φ should exceed the density of the direct radial current j_z by a factor of $\frac{\omega_e \tau_e}{1 + \omega_i \tau_i \omega_e \tau_e}$, where $\omega_e \tau_e \gg 1$.

However, measurements of the Hall current (Ref.1) based on the change in the magnetic field when the system is switched on and off, described elsewhere (Ref.1, 2), show that the value of $\chi = \frac{j_\varphi}{j_r}$ is approximately 2.

It is reasonable to assume that certain causes exist that prevent the free flow of the azimuthal current. A number of authors (Ref.3 - 5) state that the current in this system is not uniformly distributed in azimuth of the homopolar machine, but is concentrated in individual current canals that rotate like the "spokes of a wheel" (Ref.3).

2. The existence of current canals in our case was established by oscillographic study of signals from probes introduced into the interior of the homopolar machine (Fig.1), from photomultipliers (PM) onto whose cathode the image of individual regions of the system was projected (Fig.1), and from motion pictures of the discharge along the axis of a homopolar machine placed in a solenoid (Fig.2).

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* Numbers in the margin indicate pagination in the foreign text.

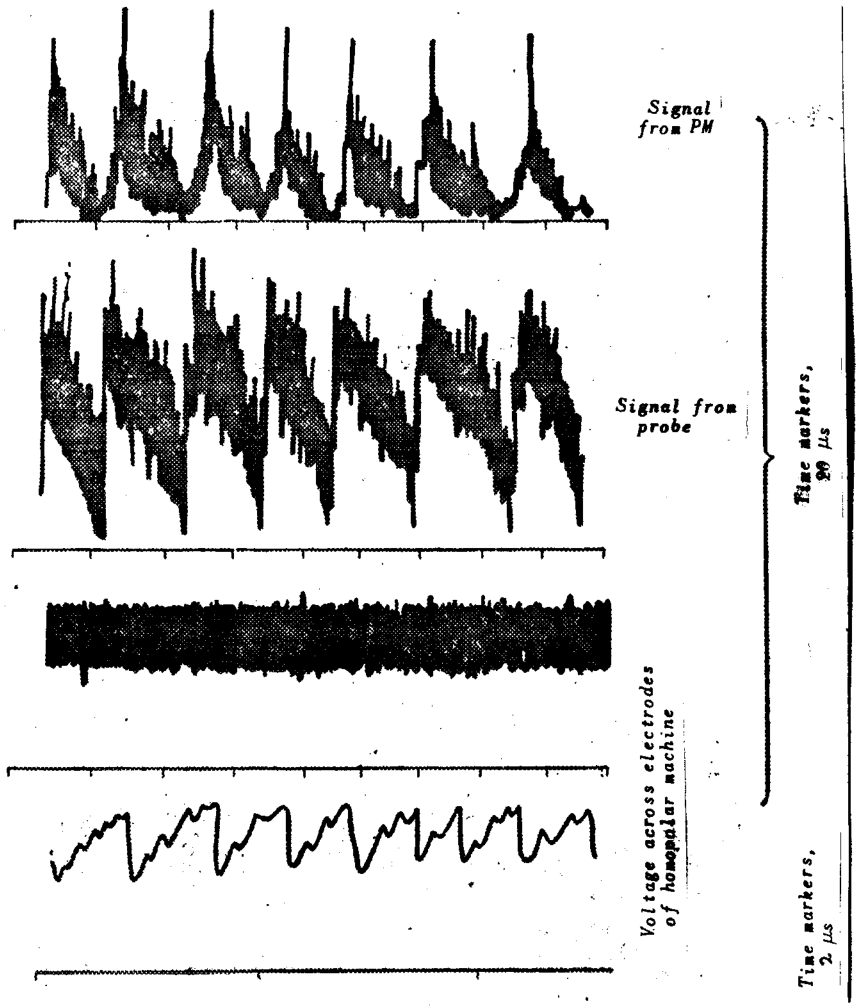

Fig.1 Oscillograms of Voltage across Electrodes of Homopolar Machine and Signals from Probe and Photomultiplier. Inner electrode - cathode; argon; I = 4.0 amp; p = 1.0 mm Hg; H = 500 oe.

We found that under these conditions there exists one current canal moving with a velocity depending on the type and density of the gas and the strength of the magnetic field (Fig.3); the current strength has only a slight effect on the motion of the current canal.

3. The development of the current canal may be represented as follows: At the instant of breakdown across the gas gap, a current canal ending in the cathode spot is formed. Since one cathode spot is entirely sufficient to provide the necessary current strength, while the formation of a new spot requires the application of a certain additional potential difference over and above that necessary to sustain the existing spot, the size of the current canal directly at the cathode is determined by the size of the cathode spot. The transverse

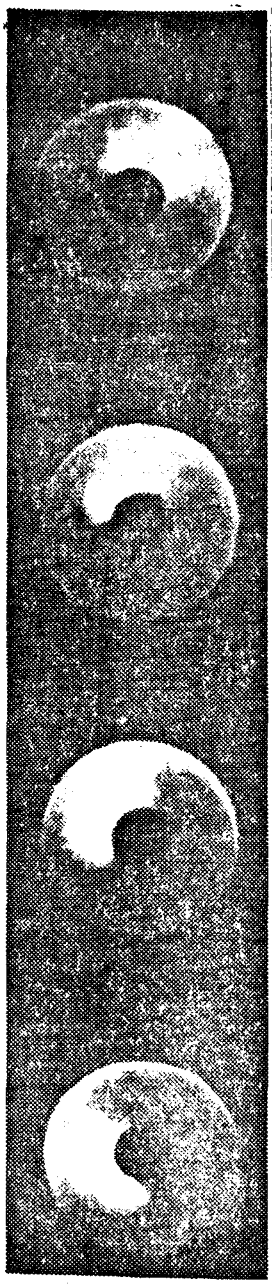

Fig.2 Motion-Picture Frames Illustrating the Character of Motion and Shape of Current Canal in Homopolar Machines
Exposure ~ 0.2 μs; time between frames ~ 2.6 μs; (inner electrode - cathode); air; I = 4.0 amp; p = 1.0 mm Hg; H = 500 oe.

dimensions of the current canal, some distance from the cathode, are determined by the diffusion of current carriers.

When the radial electric current flowing along a canal interacts with the axial magnetic field, a force $j_\varphi = \frac{1}{c} j_r H_z$ is generated /980 and discharges occur, resulting in the formation of an azimuthal Hall electric field. This field tends to equalize the velocities of azimuthal motion of electrons and ions. However, since the existing plasma configuration is three-dimensional and the electrode surface is equipotential, the magnitude of the Hall field declines in azimuthal direction, owing to the appearance of a Hall current partially closed across the electrodes and with a density, in our case, comparable to the density of the main current. As a result, the vector of total current is inclined relative to the radius of the system; the current canal will likewise have the corresponding inclination, with its anode end leading in the direction of motion of the plasma. The inclination of the plasma canal may also be affected by the lag of the cathode spot in its motion ahead of the canal.

These factors, in connection with the possibility of more complete circuit closure for the Hall current across the plasma in azimuthal direction at positive polarity (the anode region of the canal is more developed than the cathode region so that an overlap- /981 ping of the leading and trailing edges of the canal is more probable at the inner electrode which is the anode), may be explained by the observed different magnitude of the Hall current for different polarities.

The existence of a rotating current canal should not in itself cause voltage fluctuations across the electrodes of the homopolar machine. For small magnetic fields, in spite of the displacement of the plasma canal visible to the naked eye, voltage fluctuations in the external circuit are actually absent. At a certain value of the field ($H \gtrsim 500 - 1000$ oe), such fluctuations do appear. In contrast to the fluctuations taken off the probe or photomultiplier, which are caused by the passage of the current canal across the point of observation, the fluctuations in the external circuit are less ordered, have a relaxation form, and a frequency about an order higher than the frequency of rotation of the canal. When the current strength decreases to values at which the cathode spots are absent, these fluctuations disappear. It can be assumed that, at small magnetic fields, the velocity of rotation of the current canal is rather small, and the spot is able to follow the canal. When this rotational velocity is higher, the cathode spot will lag behind the canal, it will be drawn out, the voltage across the electrodes will rise, and breakdown will occur, with the formation of a new cathode spot on the electrode surface; the plasma canal in this case remains as before. In some cases, however, it is not excluded that a new plasma canal may be formed.

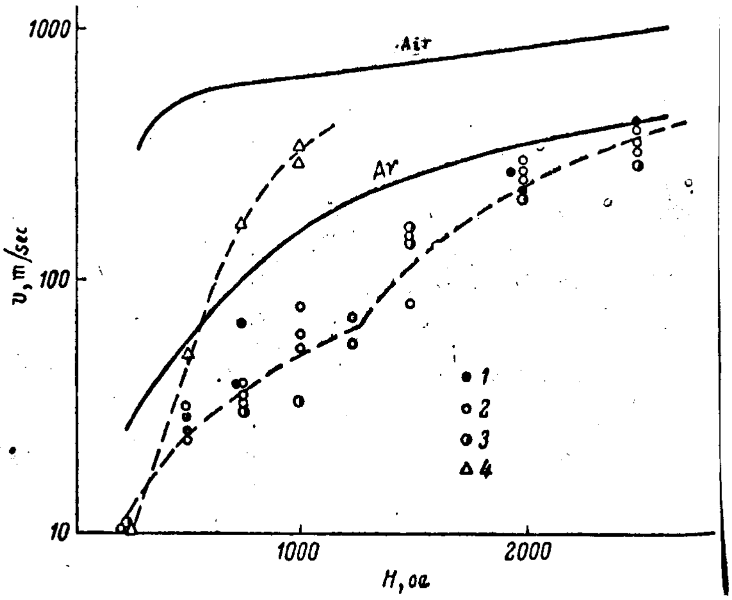

Fig.3 Relation between Velocity of Plasma and Strength of the Magnetic Field.
Heavy curves - theoretical; 1 - air, p = 1.0 mm Hg; 2, 3, 4 - argon, p = 1.0, 0.5, 0.25 mm Hg (inner electrode cathode; I = 4.0 amp).

4. A plasma theory of the current canal must primarily include a consideration of the spatial current distribution, including current flow into the electrode, which is a complex problem even if the distribution of conductivity is known. Following Eninger (Ref.6), we may consider a simplified model of the motion of a plane plasma front through a neutral gas in crossed electric and magnetic fields. The concentration of charge carriers is assumed to be far smaller than the concentration of stationary neutral molecules. The constant electric field E_y and the constant magnetic field $H = H_z$ are considered as given. The problem is to find the translational velocity of the plasma, equal to the velocity of the ions, in the direction of the x axis.

Neglecting the inertia terms and the influence of the pressure gradients, we have four equations of motion of the electron and ion components in homogeneous crossed fields:

$$\frac{m_i}{\tau_i} v_{ix} = eE_x + \frac{e}{c} v_{iy} H,$$

$$\frac{m_i}{\tau_i} v_{iy} = eE_y - \frac{e}{c} v_{ix} H,$$

$$\frac{m_e}{\tau_e} v_{ex} = - eE_x - \frac{e}{c} v_{ey} H,$$

$$\frac{m_e}{\tau_e} v_{ey} = - eE_y + \frac{e}{c} v_{ex} H.$$ /982

The necessary fifth equation is obtained by taking the experimental ratio of the density of the Hall current to the density of the forward current:

$$\chi = \frac{j_x}{j_y} = \frac{j_{ix} + j_{ex}}{j_{iy} + j_{ey}} = \frac{v_{ix} - v_{ex}}{v_{iy} - v_{ey}}.$$

The value of χ may vary from zero in the case of no Hall current (Ref.6) to $\chi_{max} = - \frac{\omega_e \tau_e}{1 + \omega_i \tau_i \omega_e \tau_e}$ for a completely homogeneous plasma at independent motion of the ion and electron components. In our case, $\chi = 1 - 2.5$ (Ref.1).

Solving the equations for v_{ix} we obtain (taking into account that $\omega_e \tau_e \gg \omega_i \tau_i$)

$$v_{ix} = \frac{cE}{H} \frac{\omega_i \tau_i (\omega_e \tau_e + \chi)}{1 + \omega_i \tau_i \omega_e \tau_e - \chi(\omega_e \tau_e)}.$$

5. For our discharge parameters ($\omega_e \tau_e \gg 1 \gg \omega_i \tau_i$) and values of χ we have

$$v_{ix} = - \frac{cE}{H} \frac{\omega_i \tau_i}{\chi}.$$

The values predicted by this formula are compared in Fig.3 with the experimentally determined velocity of the current canal, for the mean radius of the system (R_1 = 3.4 cm, R_2 = 9.8 cm, R_{av} = 6.6 cm). To calculate the value of τ_i, we used data on the ionic mobility in an electric field (Ref.7); the temperature of the neutral gas was taken as 700°K (Ref.2); the strength of the electric field was measured by the aid of a double probe with a static voltmeter (Ref.8). /983

The agreement of the experimental data with the theoretical values can be considered satisfactory only for argon; for air, the theory gives a considerably higher velocity. Only at high magnetic field strength do the experimental values approach the theoretical.

Experiments likewise show that the current canal velocity depends less on the gas density than might have been expected.

It may therefore be assumed that, under the conditions considered, the velocity of the plasma canal is limited mainly by the rate of displacement of the cathode spot on the electrode. The resistance of the neutral gas to the motion of the plasma becomes decisive only at H $\gtrsim$ 1000 oe.

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